Experimental Investigation and Modelling of Hazardous Incidents in Liquid Helium Cryostats

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KSETA Plenary Workshop 2016, Durbach

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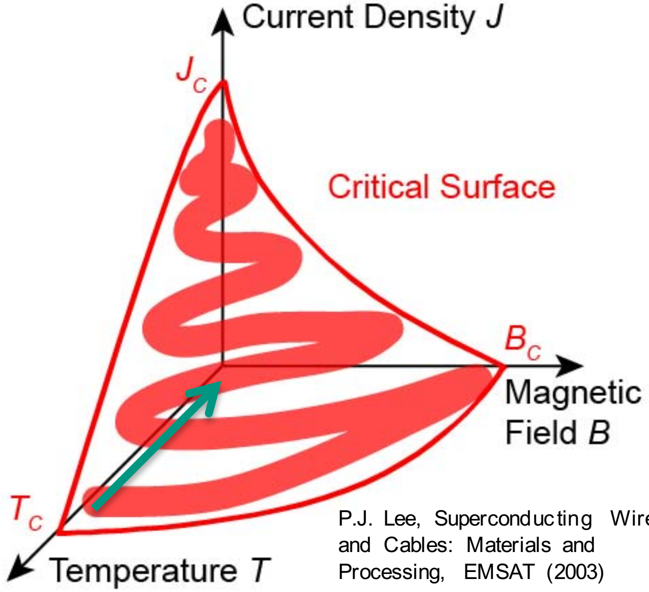
Motivation: Superconductivity

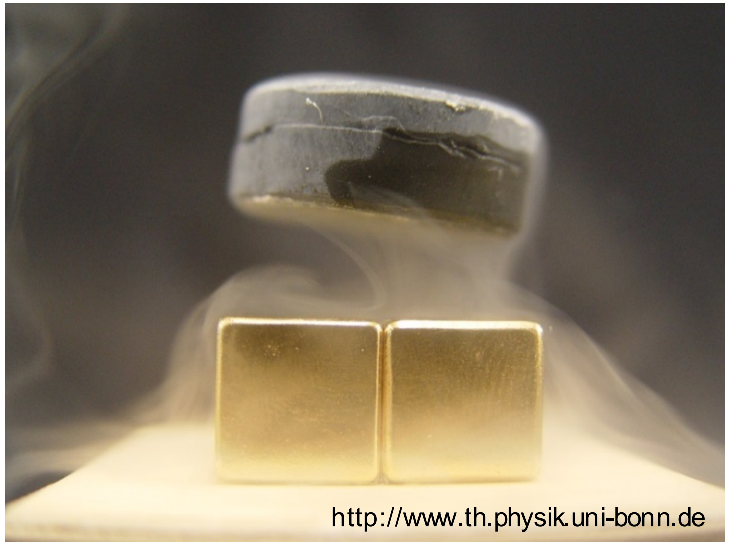
- Conventional conductors: el. resistance → heat → large energy losses
- Superconductors → materials with $R = 0\,\Omega$ for low J, B, T
- Application: sc. cables, sc. magnets
  - For $J \uparrow, B \uparrow \rightarrow T \downarrow$

➡ Cooling with LHe



P.J. Lee, Superconducting Wires and Cables: Materials and Processing, EMSAT (2003)

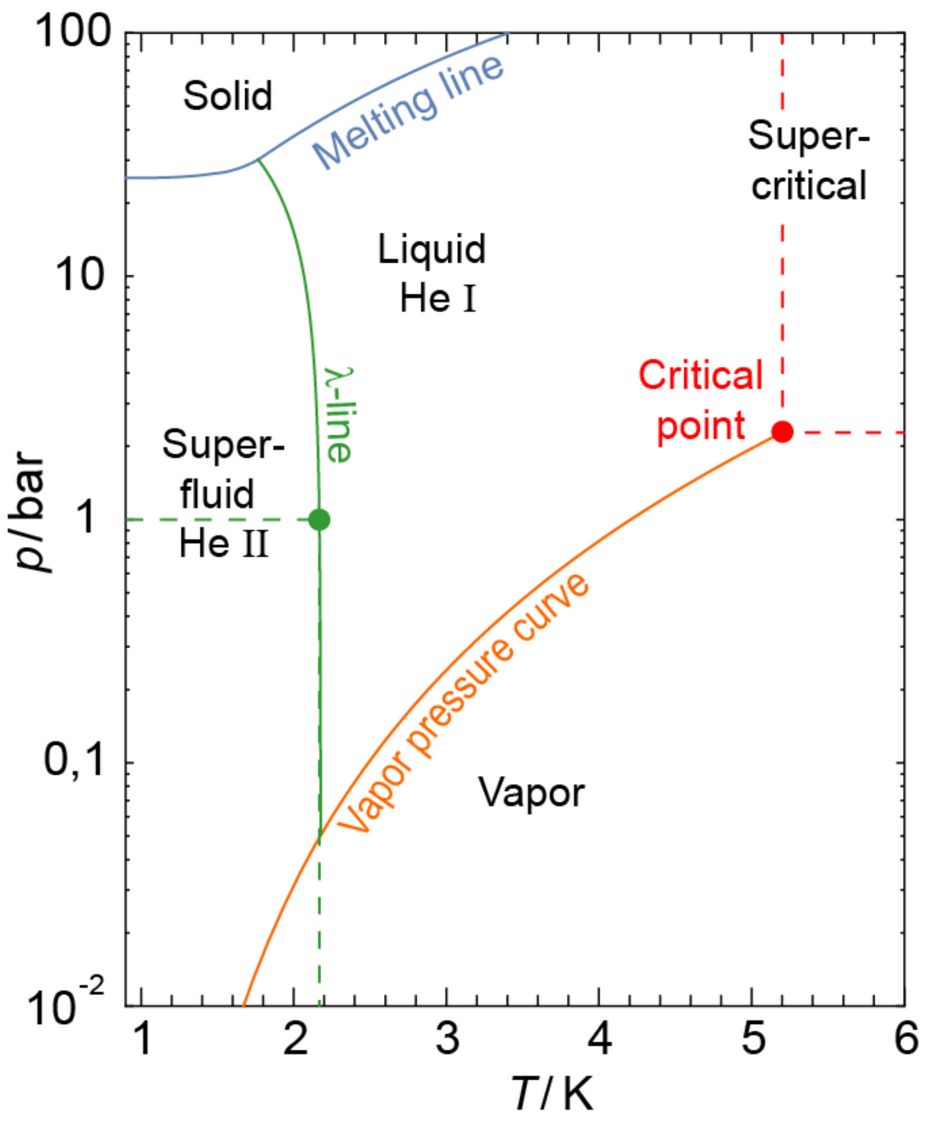
http://home.web.cern.chr



http://www.th.physik.uni-bonn.de

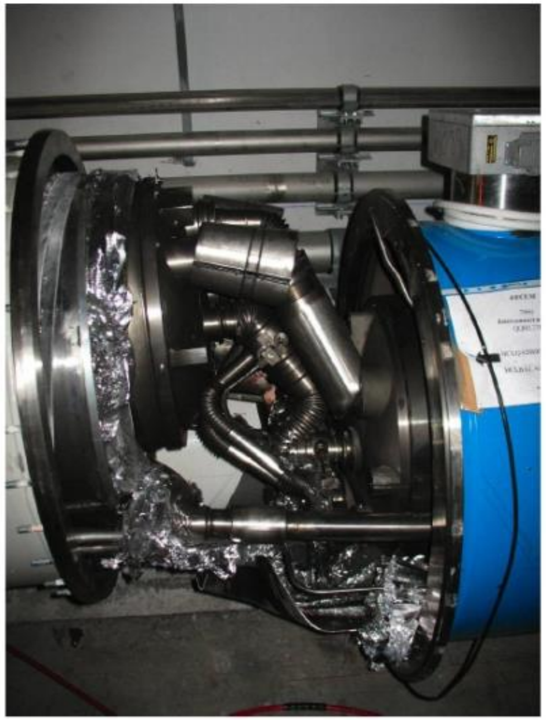
Motivation: Helium

- Two stable isotopes: ^{3}He and $\mathbf{^4He}$
- Normal boiling point $T_{\mathrm{nb}} = 4.2\ \mathrm{K}$
- Lowest critical point of all fluids:
  - $T_{\mathrm{c}} = 5.195\ \mathrm{K}$
  - $p_{\mathrm{c}} = 2.27\ \mathrm{bar}$
- No solid state at any temperature at $p < 25\ \mathrm{bar}$
- Superfluid at $T < T_{\lambda}$
  - $T_{\lambda}(1\ \mathrm{bar}) = 2.17\ \mathrm{K}$
- Enthalpy of evaporation $\Delta h_{\mathrm{V}}(4.2\ \mathrm{K}; 1\ \mathrm{bar}) = 2.6\ \mathrm{kJ/l}$
  - Factor 835 lower than water
  - Factor 62 lower than nitrogen



Motivation: Incident LHC 09/2008

- Quench of sc. connection → electrical arc → puncture of helium enclosure → vacuum breakdown
- Safety devices too small → damage by overpressure
- Delay >1year, costs several million €



Sources:
http://press.web.cern.ch/press-releases/2008/10/cern-releases-analysis-lhc-incident

https://cds.cern.ch/record/1185822

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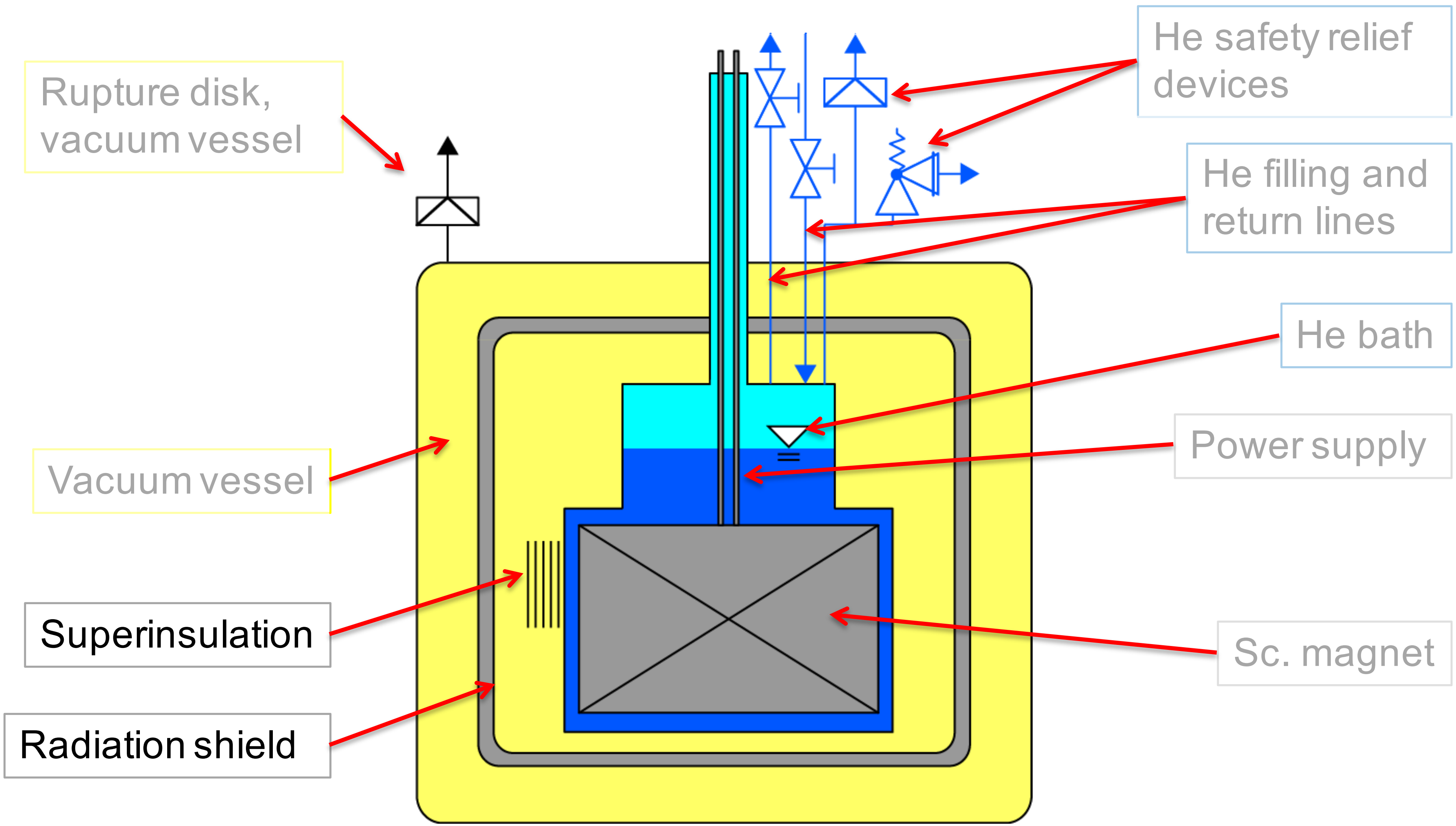
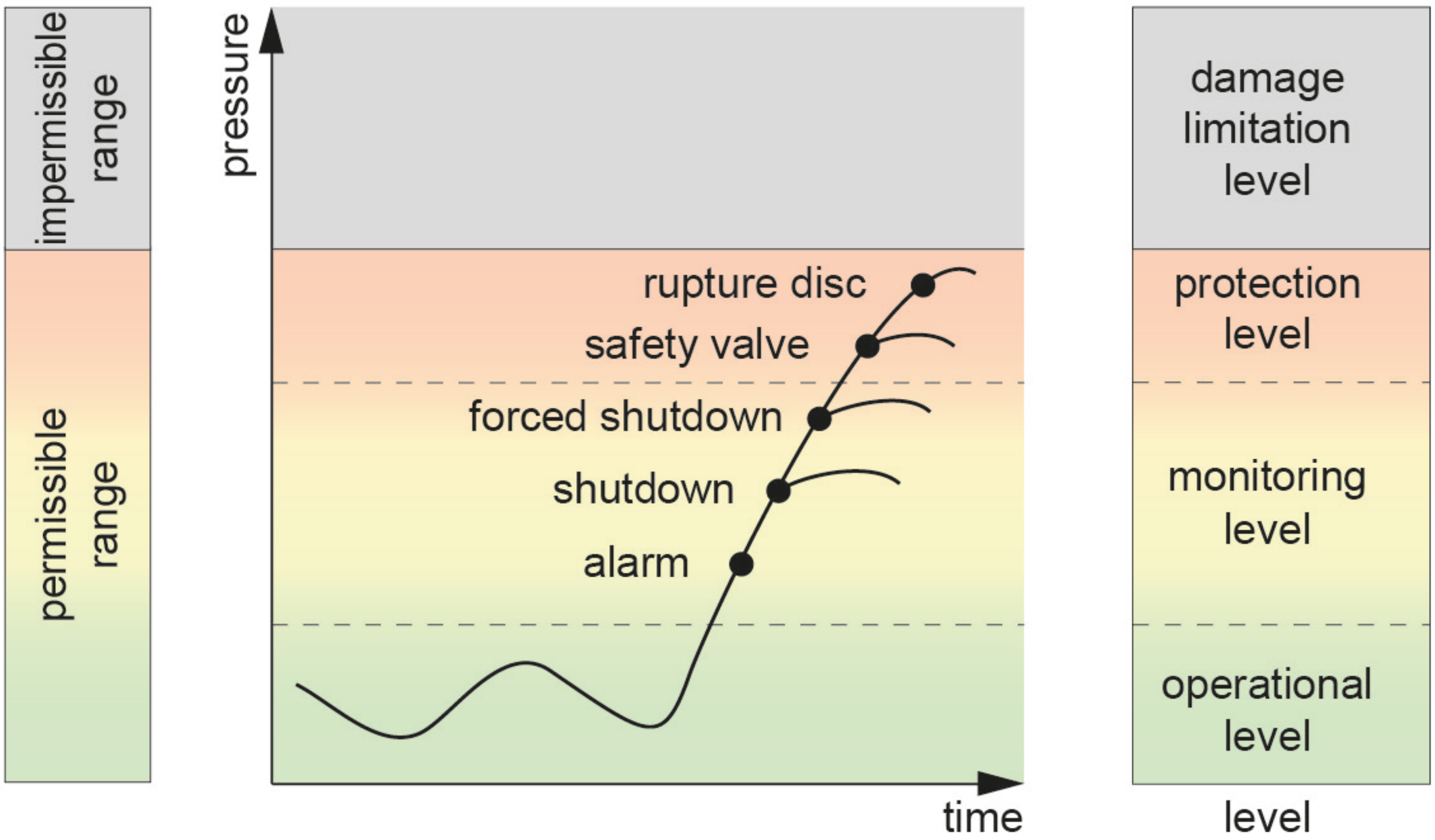
Motivation: Helium Safety

Helium Bath Cryostat



Source: DIN SPEC 4683:2015-04 *Cryostats for liquefied helium – Safety devices for protection against excessive pressure*

Safety Concept



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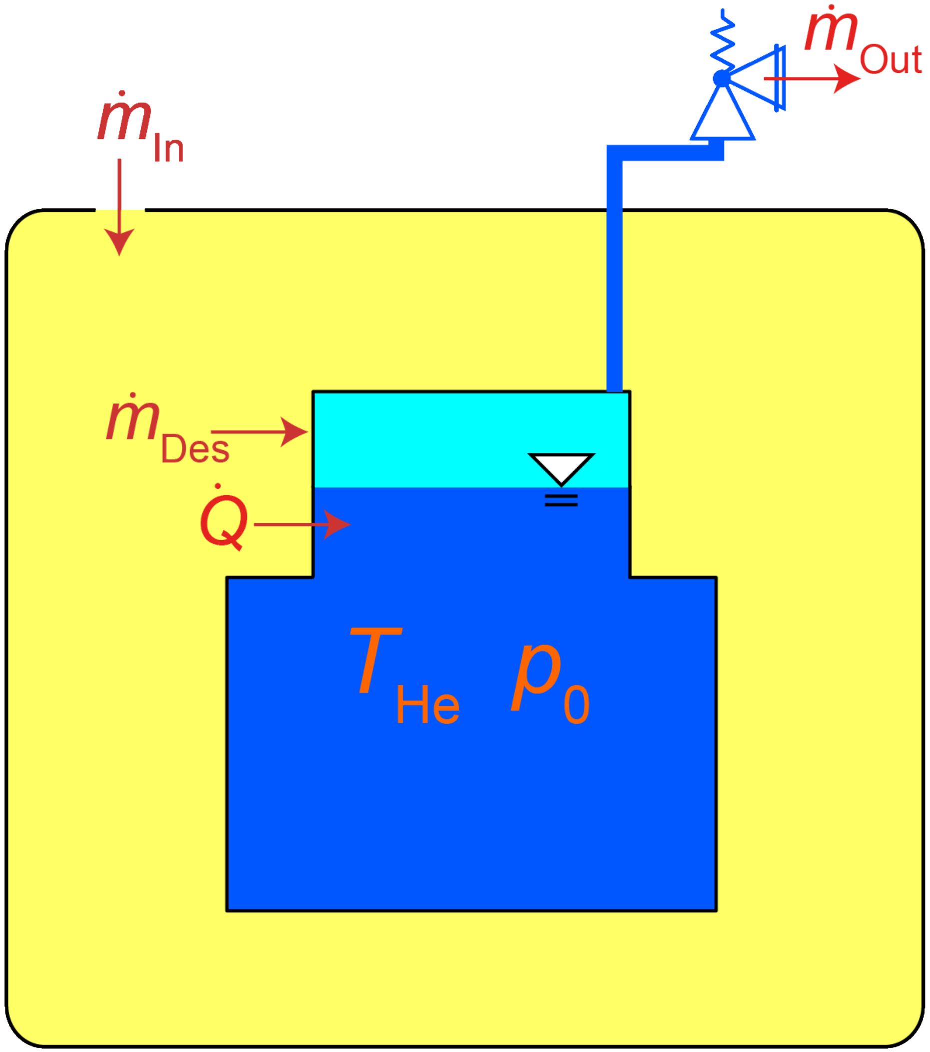
Example Hazardous Incident



Dimensioning of cryogenic safety relief devices

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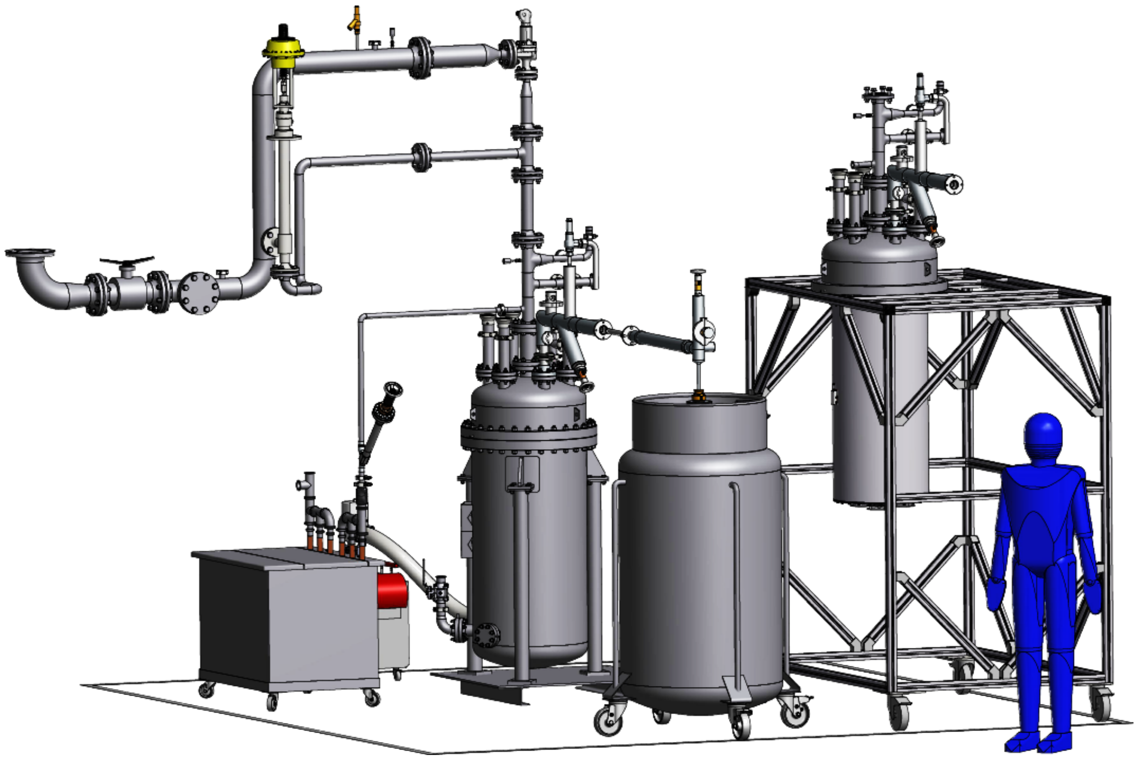
- Dimensioning for **worst case**: venting of insulating vacuum with atmospheric air
- Existing models and standards (e.g. DIN EN 13648) do not consider **process dynamics** → $\dot{q} = \mathrm{const.}$ [1]
  - **Oversizing** of safety valves
  - Implications on spending, space and helium leakage
- **Dynamic model** links all time-dependent sub-processes [2]
  - ODE system based on thermodynamic and fluid mechanic principles
  - Contains some simplifications (desublimation, kinetics)
  - Experiments for validation and extension of model → **fit parameters**

[1] Lehmann, W., Zahn, G., Safety aspects for LHe cryostats and LHe transport containers, 1987 *Proc. Int. Cryog. Eng. Conf.* **7** 569-579
[2] Heidt, C., Grohmann, S., Süßer, M., Modeling the Pressure Increase in Liquid Helium Cryostats after Failure of the Insulating Vacuum, 2014 *AIP Conf. Proc.* **1573** 1574-1580

PICARD

- Purpose & Operating Range
- Design & Construction
- First Results
- Status & Outlook



Purpose & Operating Range PICARD

- Test facility PICARD: **P**ressure **I**ncrease in **C**ryostats and **A**nalysis of **R**elief **D**evices
  - Cryogenic liquid volume: **100 liters**
  - Nominal design pressure: **16 bar(g)**
  - Helium discharge mass flow rates: up to about **4 kg/s**
- **Broad range** of experiments with cryogenic fluids in cooperation with CERN [3]
  - **Heat flux** and **flow rate** measurements under various conditions
  - Studies on the impact of **two-phase flow**
  - Measurement of **flow coefficients** of safety devices at 4…300 K

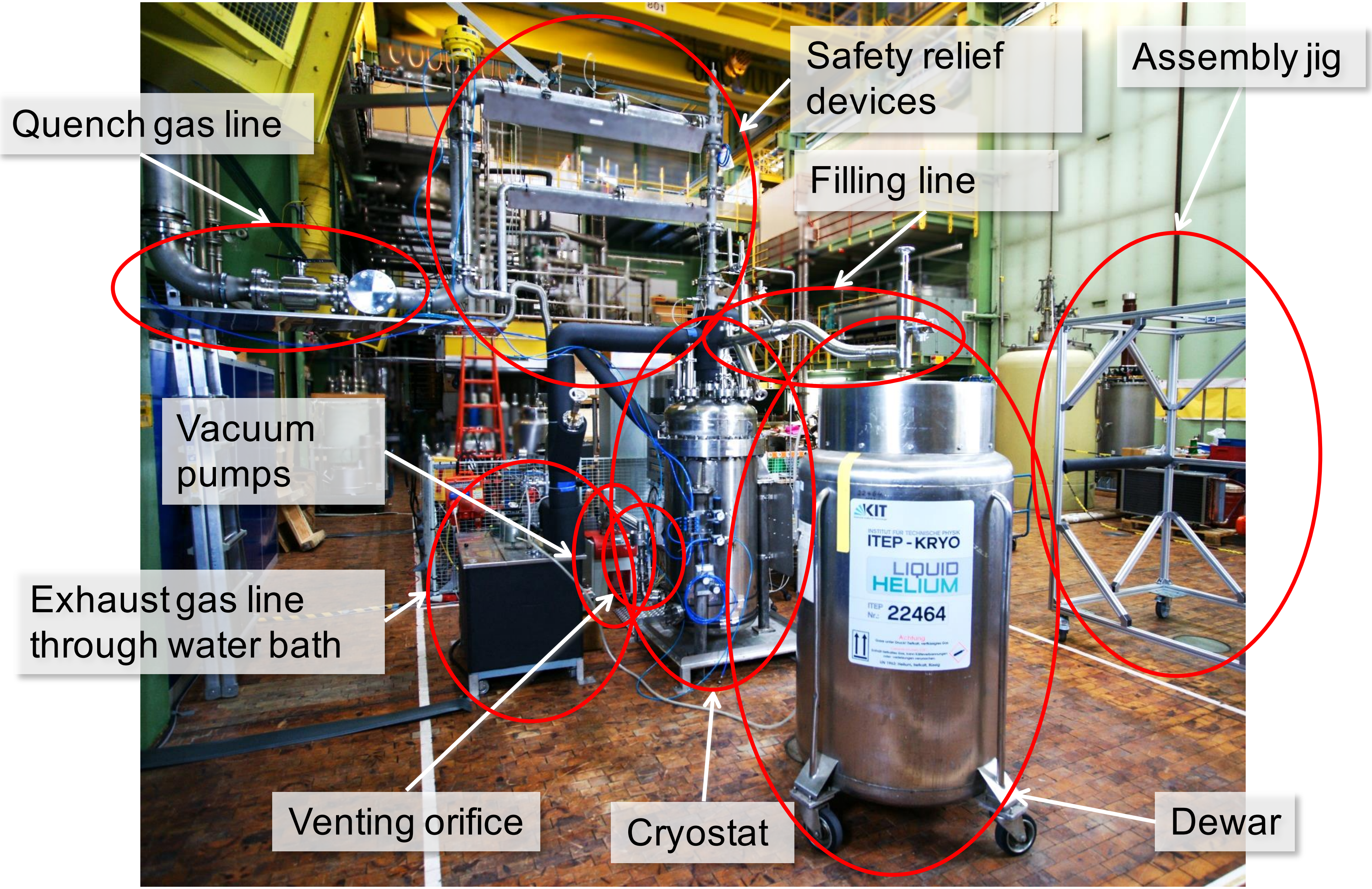
[3] Collaborative R&D on experimental testing on cryogenic pressure relief between CERN and KIT, KE2974/KT/DGS/222C,12/2015

Purpose & Operating Range

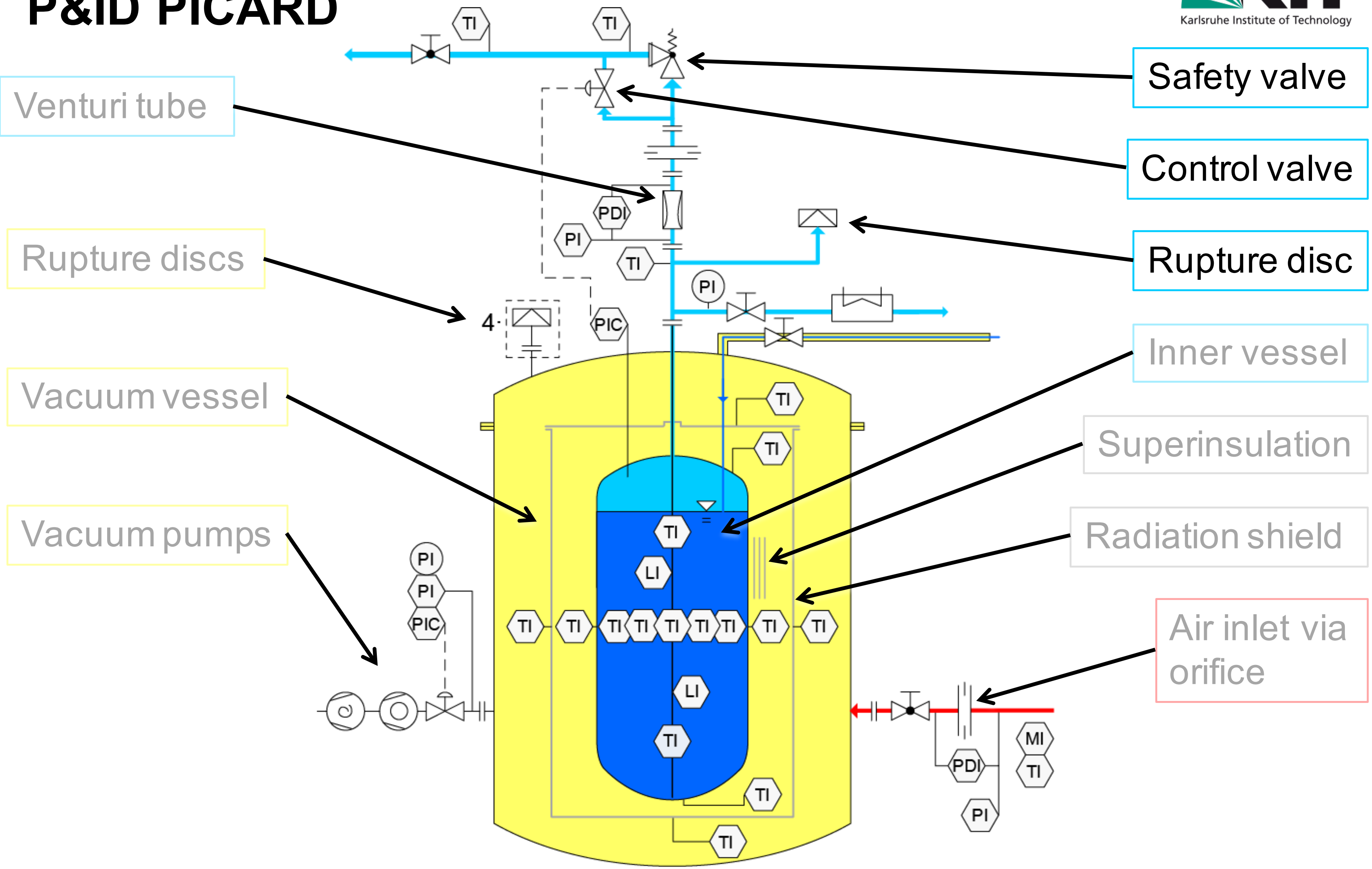
Variation of	Range
Venting diameter	1…40 mm
Insulation	0…30 layers of superinsulation, with/without radiation shield
Liquid level	20…80 %

[4] Heidt, C., Schön, H., Stamm, M., Grohmann, S., Commissioning of the cryogenic safety test facility PICARD, 2015, *IOP Conf. Ser.: Mater. Sci. Eng.* **101**, 012161

Safety Test Facility PICARD



P&ID PICARD



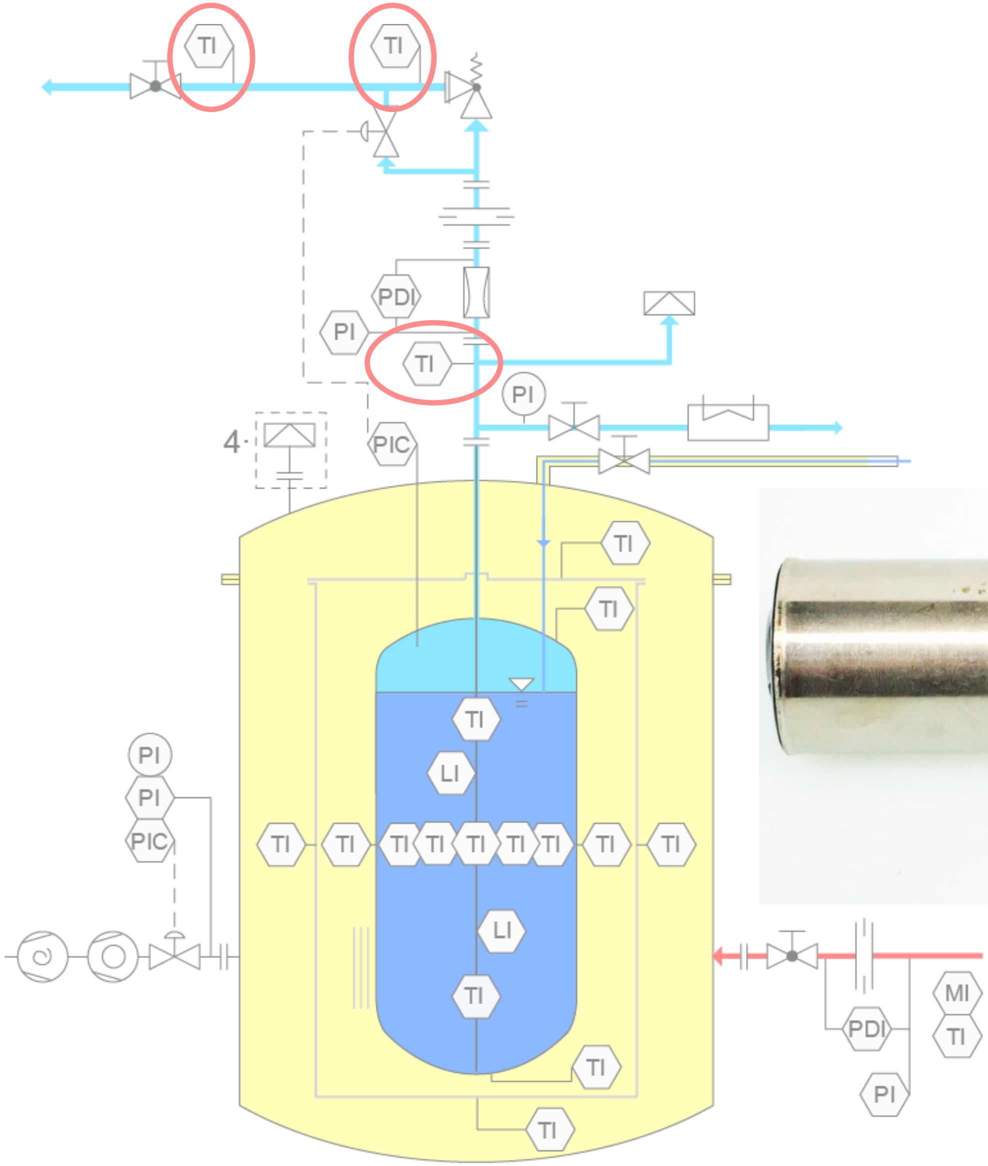
Safety valve
Venturi tube
Control valve
Rupture discs
Rupture disc
Vacuum vessel
Inner vessel
Superinsulation
Vacuum pumps
Radiation shield
Air inlet via orifice
TI
PDI
PI
PIC
LI
MI
4

Surface Temperature Measurement

0.9 m

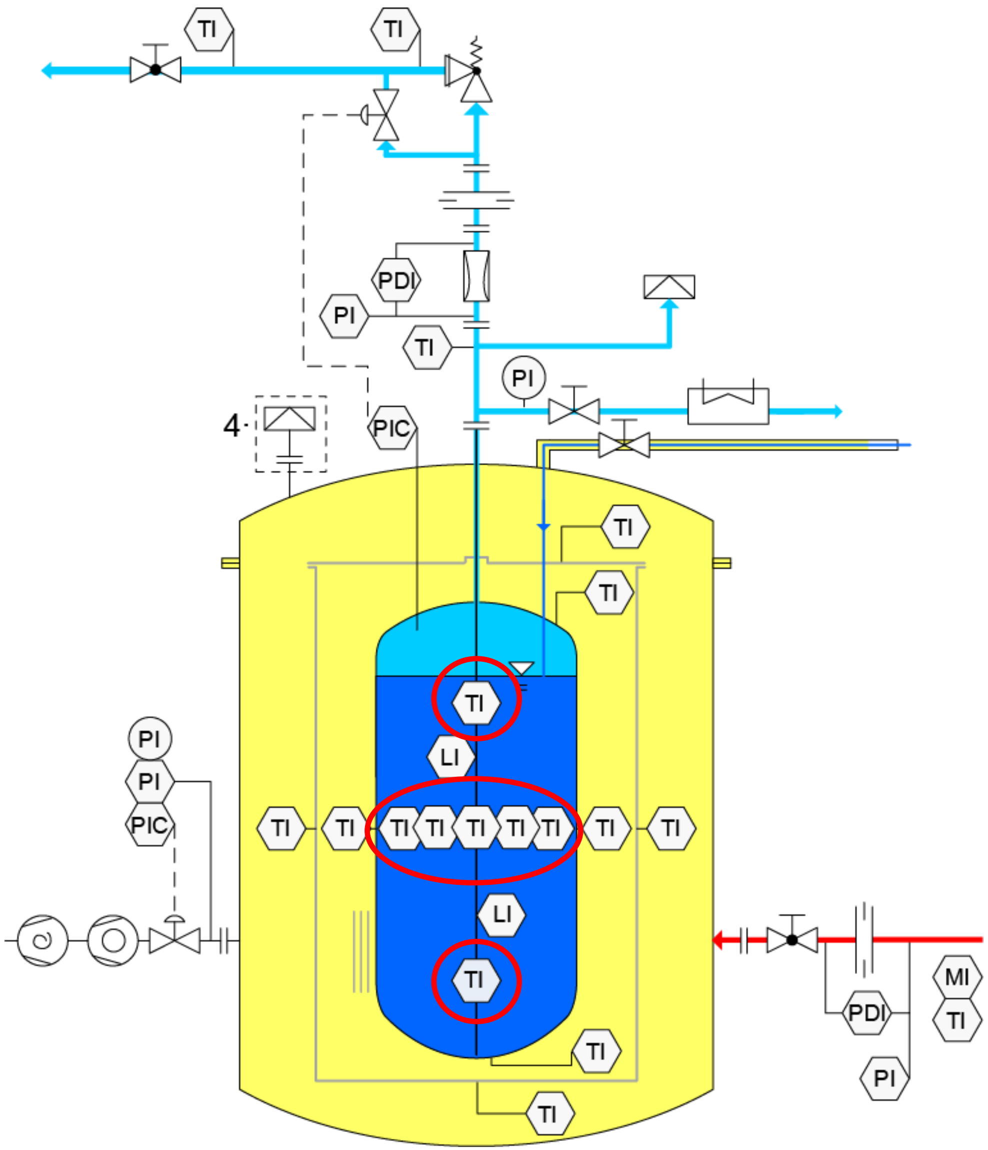
TVO sensor in copper sleeve

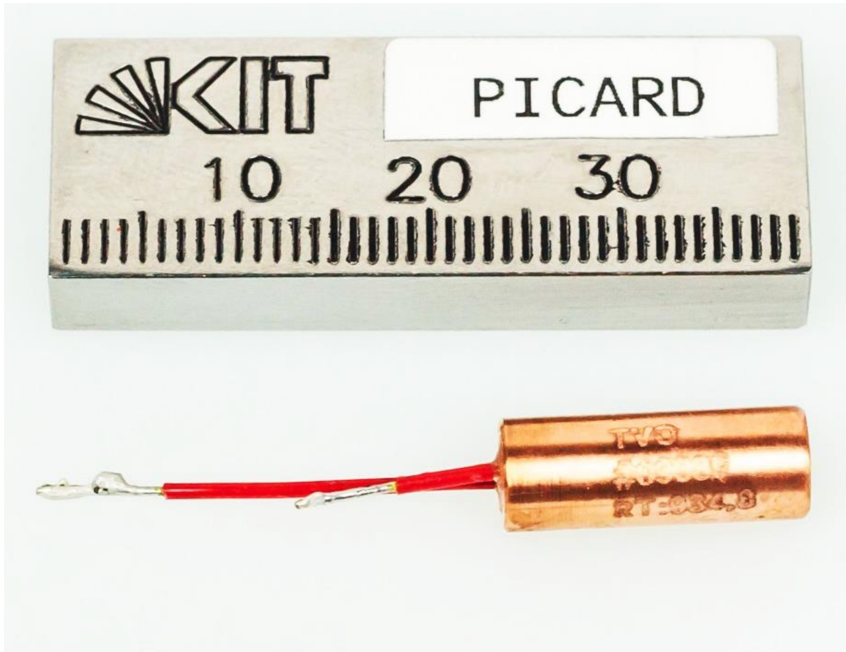
Flow Temperature Measurement



TVO sensor in copper sleeve

Fast Temperature Measurement





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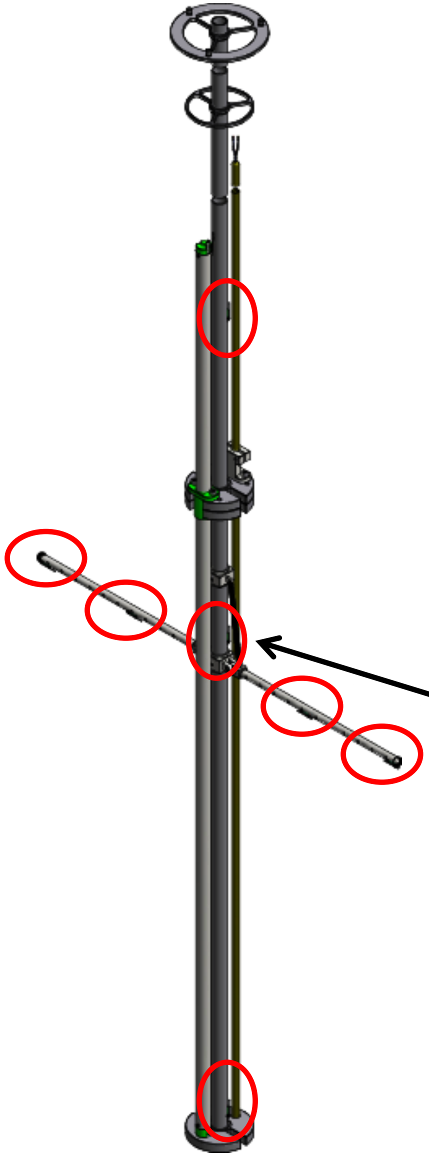
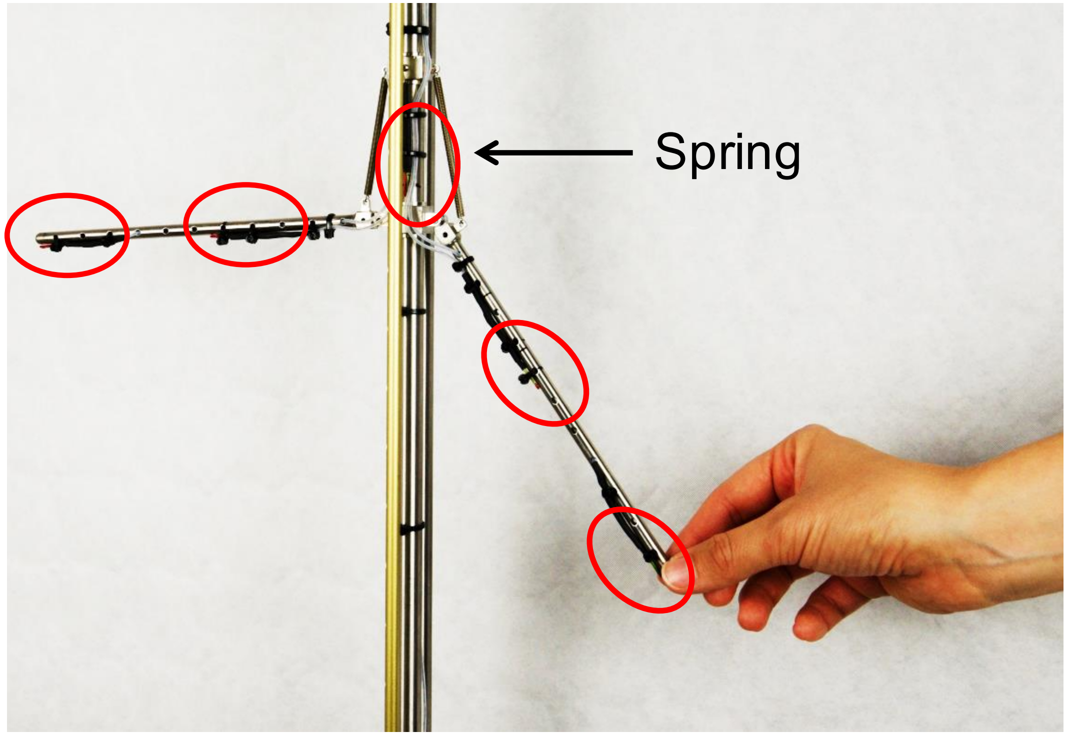
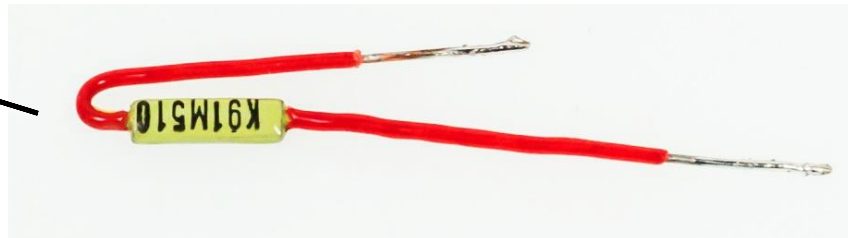
Fast Temperature Measurement

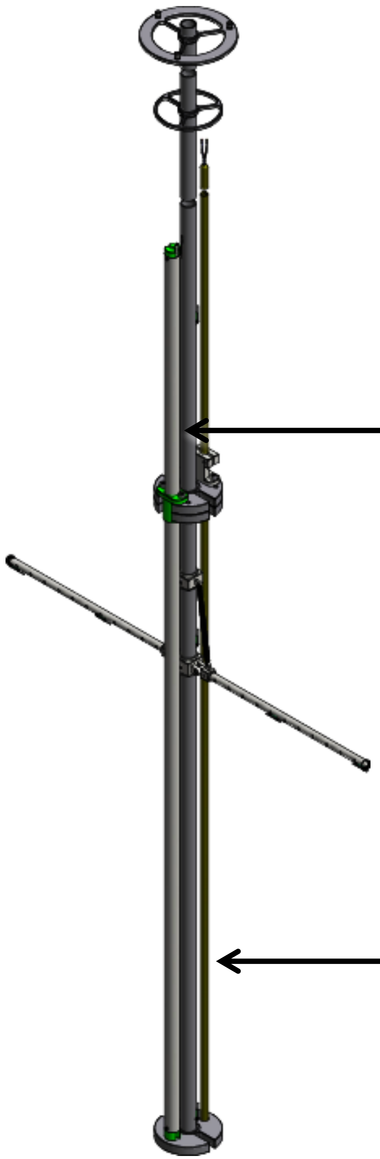






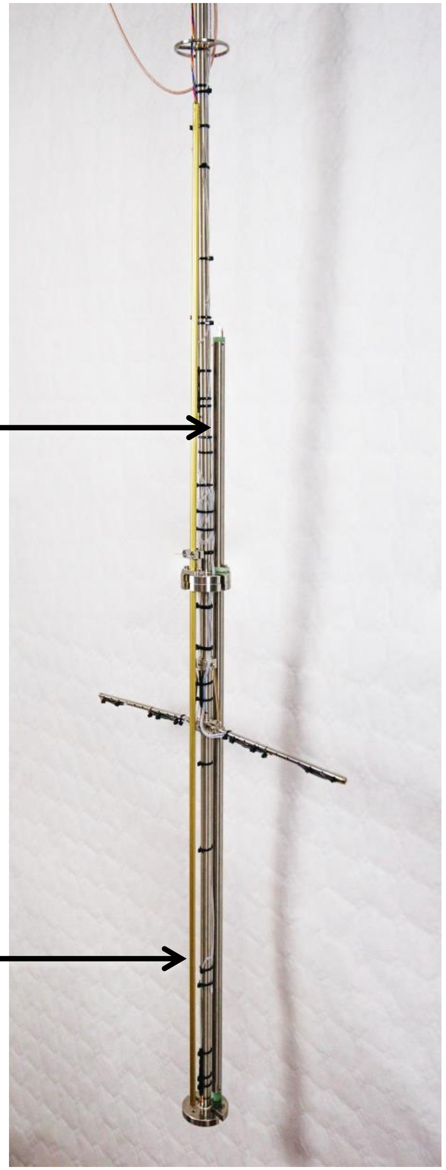
Plain TVO sensor

Level Measurement



Capacitive level sensor

Superconducting level sensor



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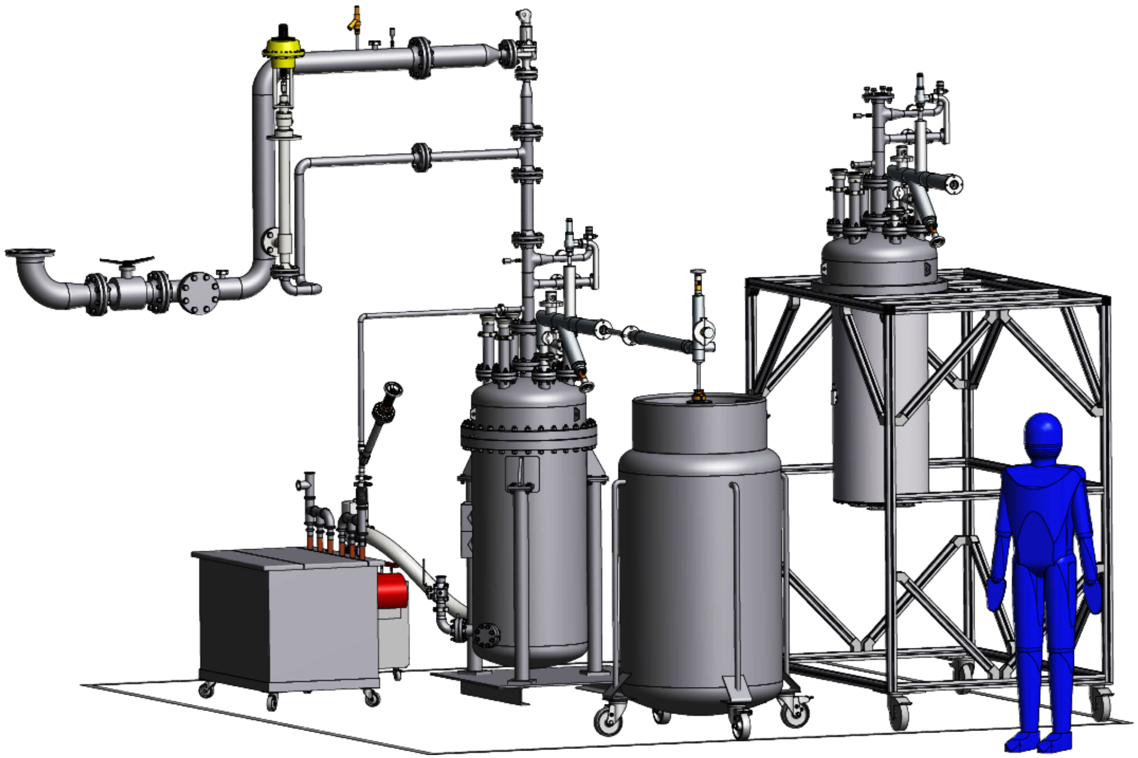
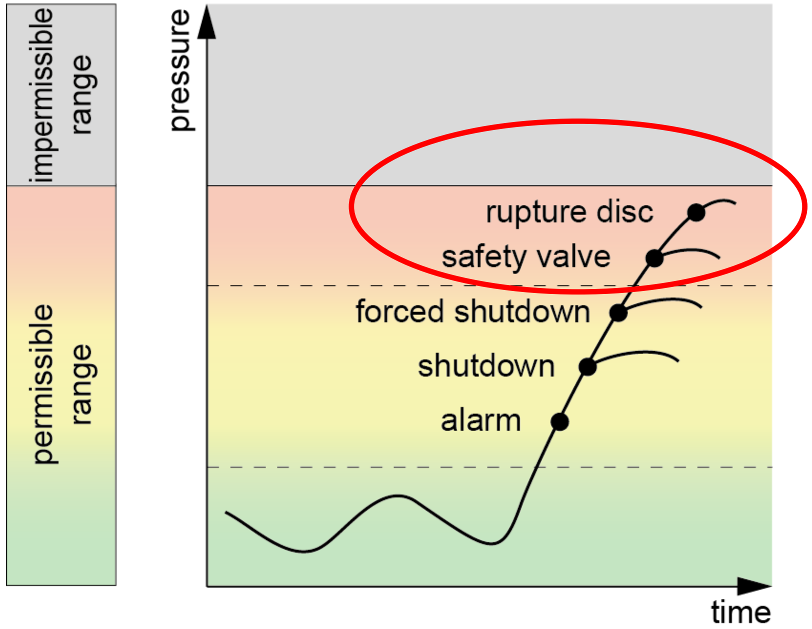
PICARD

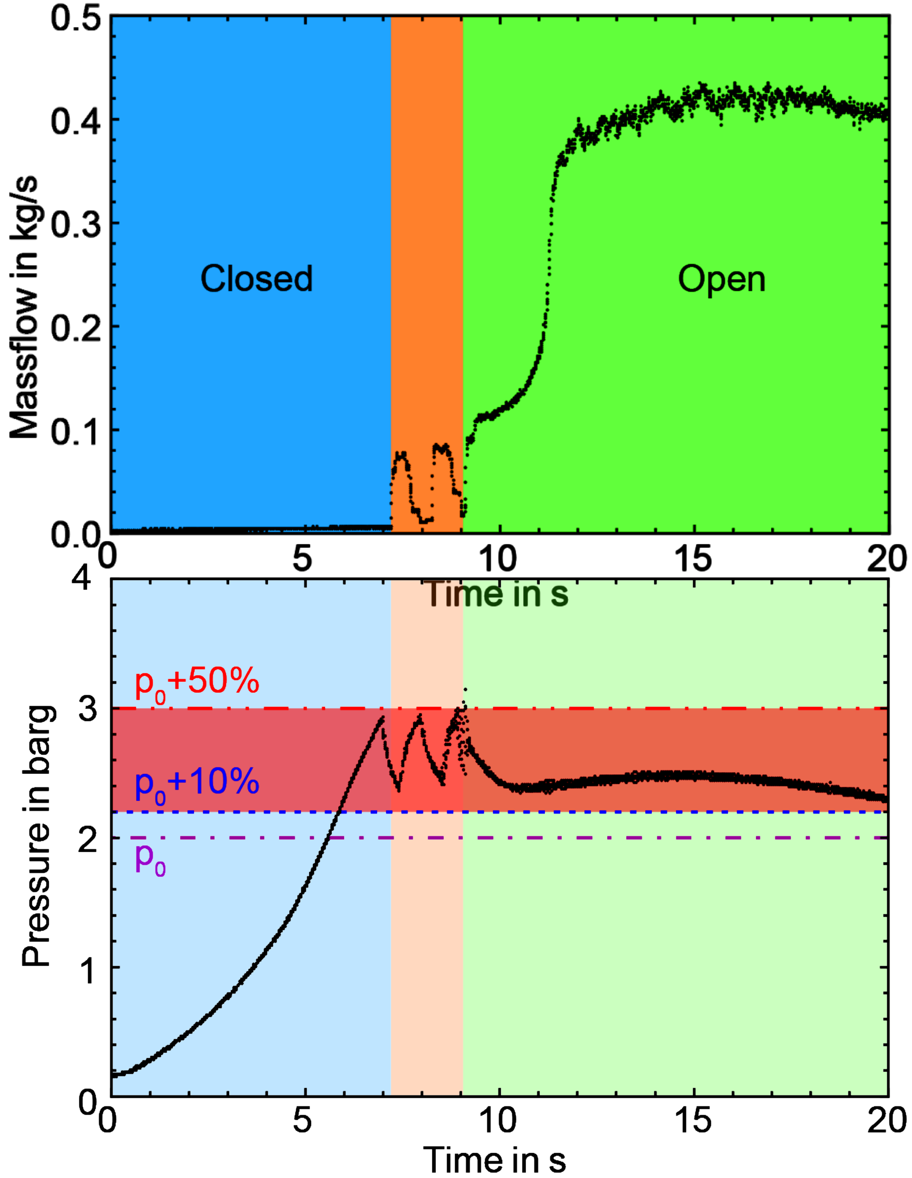
- Purpose & Operating Range
- Design & Construction
- **First Results**
- Status & Outlook



Results of First Venting Experiments

- Venting with atmospheric air
- Venting diameter: 12.5 mm
- Set pressure safety valve: 2 barg
- Filling level: ~50%
- Liquid He volume: 59 l





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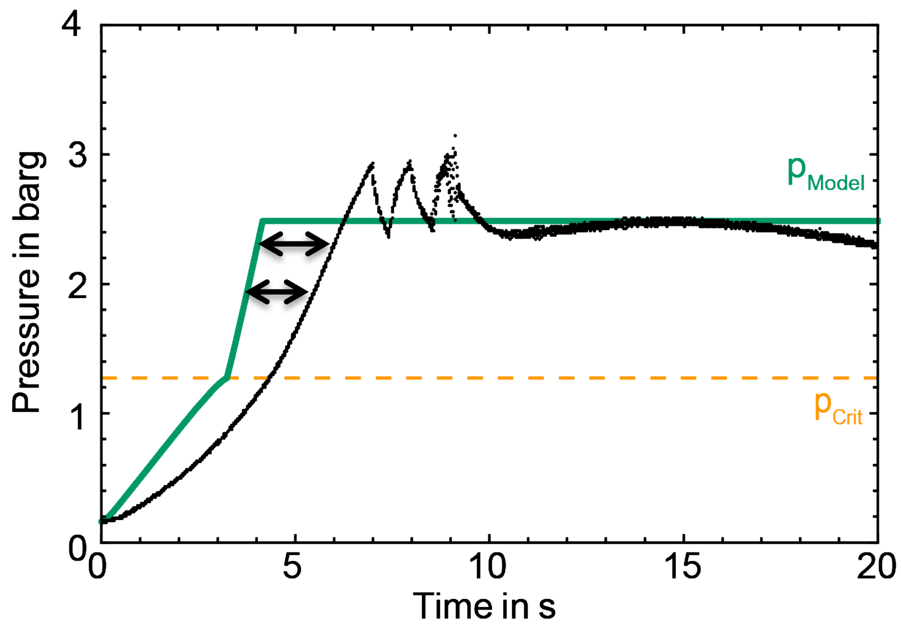
Results of First Model Fitting

- Venting with atmospheric air
- Venting diameter: 12.5 mm
- Set pressure safety valve: 2 barg
- Filling level: ~50%
- Liquid He volume: 59 l

- Set pressure model: 2.5 barg
- Desublimation fittet → absolute values correspond well
- Time difference → heat transmission resistance



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Status & Outlook PICARD

- Design & Construction ✓
- Commissioning ✓
  - Pressure and leak test
  - Instrumentation
- Experiments ✓
  - Venting with nitrogen and air
  - Small venting diameters
  - Low set pressures
  - Without superinsulation
- Parameter fit model
  - Desublimation ✓
  - Kinetics ✓
- Planned experiments:
  - Larger venting diameters
  - Higher set pressures
  - With other cryogenic fluids
  - Simulation of magnet quench
- Investigation of
  - Safety valve behavior at cryogenic temperatures
  - Two-phase flow

Outlook?

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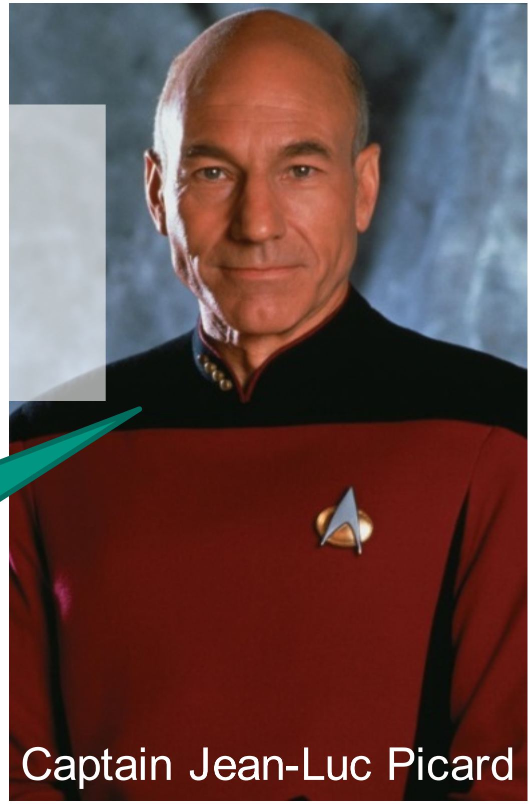
Do you think this is a wise course of action, sir?

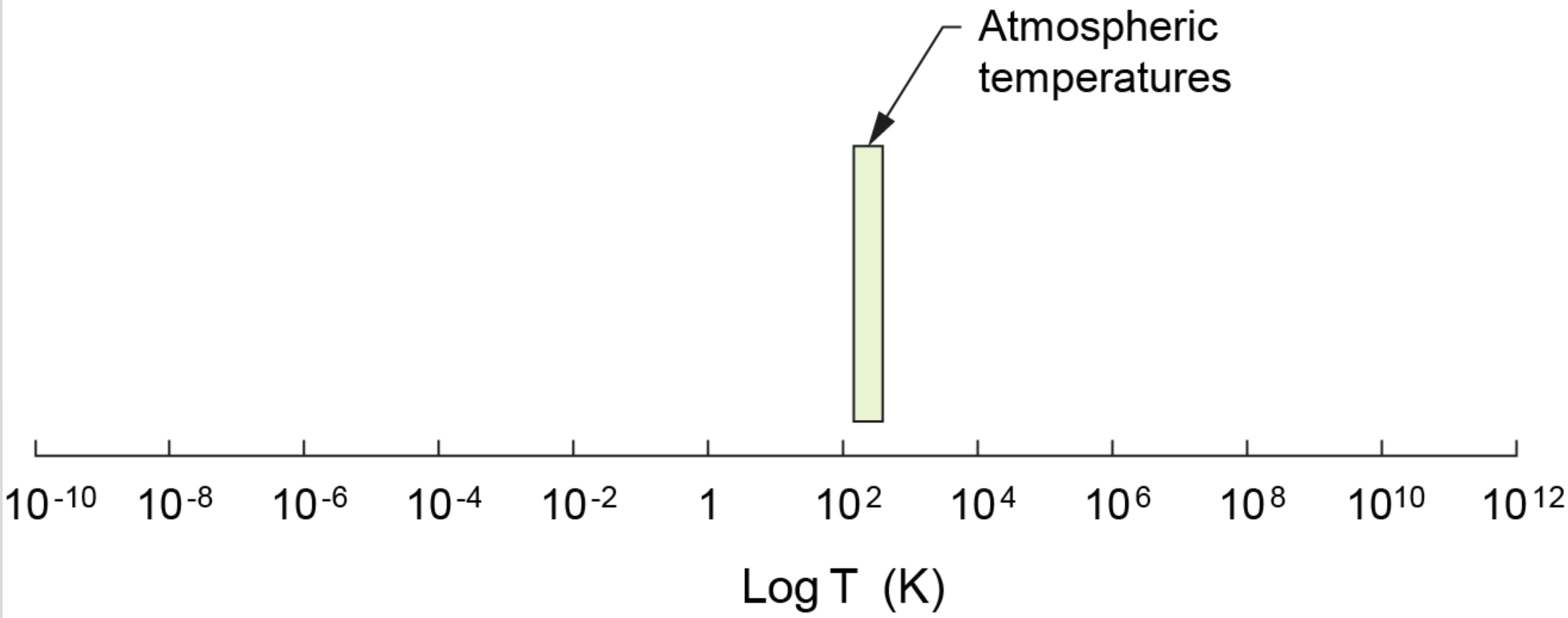
Thank you for your attention!



We're about to find out, Data.

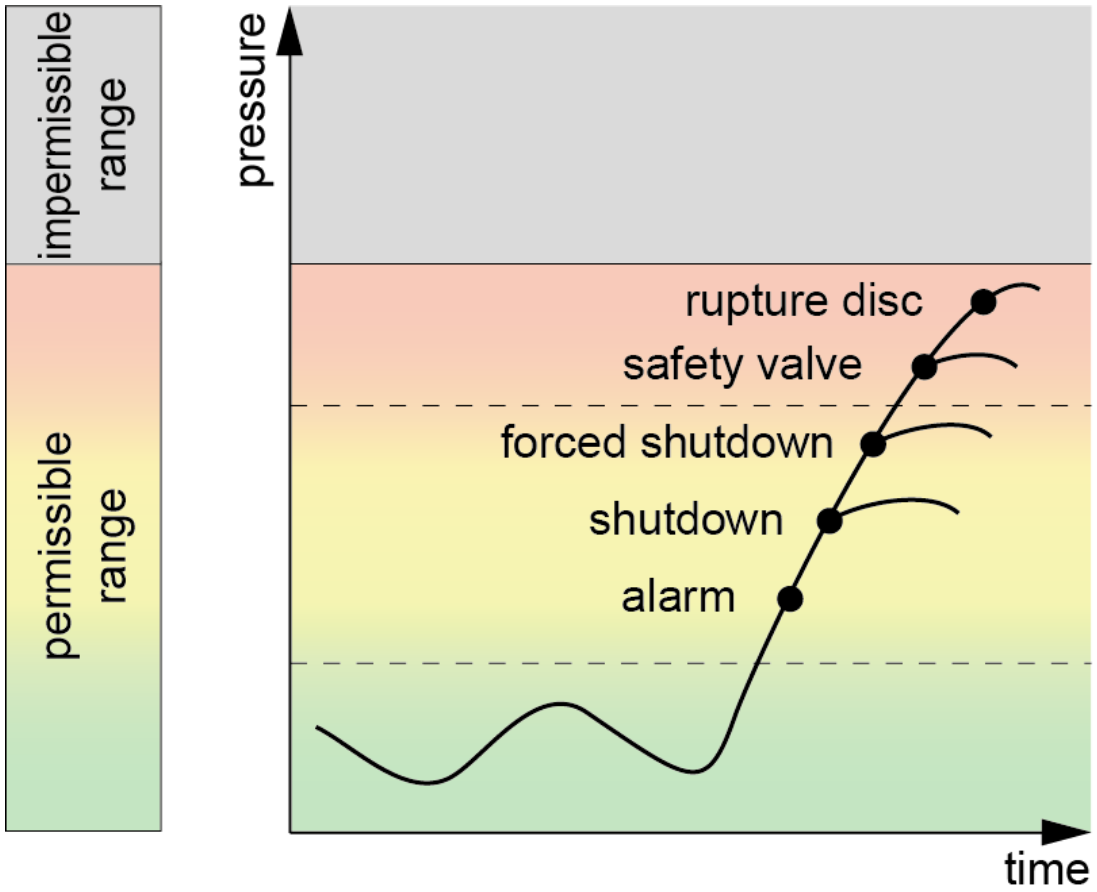
Citation: IMDb, *Quotes for Captain Jean-Luc Picard (Character) from Star Trek: The Next Generation (1987)*, Star Trek - Nemesis (2002), Paramount Pictures, http://www.imdb.com/character/ch0001449/quotes- access: 2015/08/13
Pictures: www.moviepilot.de

Cryogenics



Thank you for your attention!

Safety Concept



measure	level
air monitoring exhaust gas line shuttle valve	damage limitation level
independent of auxiliary energy	protection level
pressure switch SPS SPS	monitoring level
control	operational level

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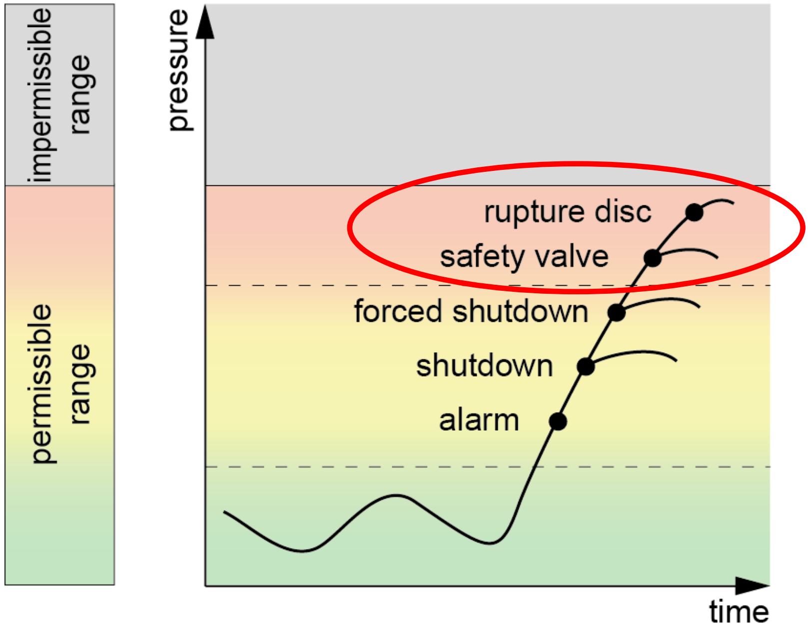
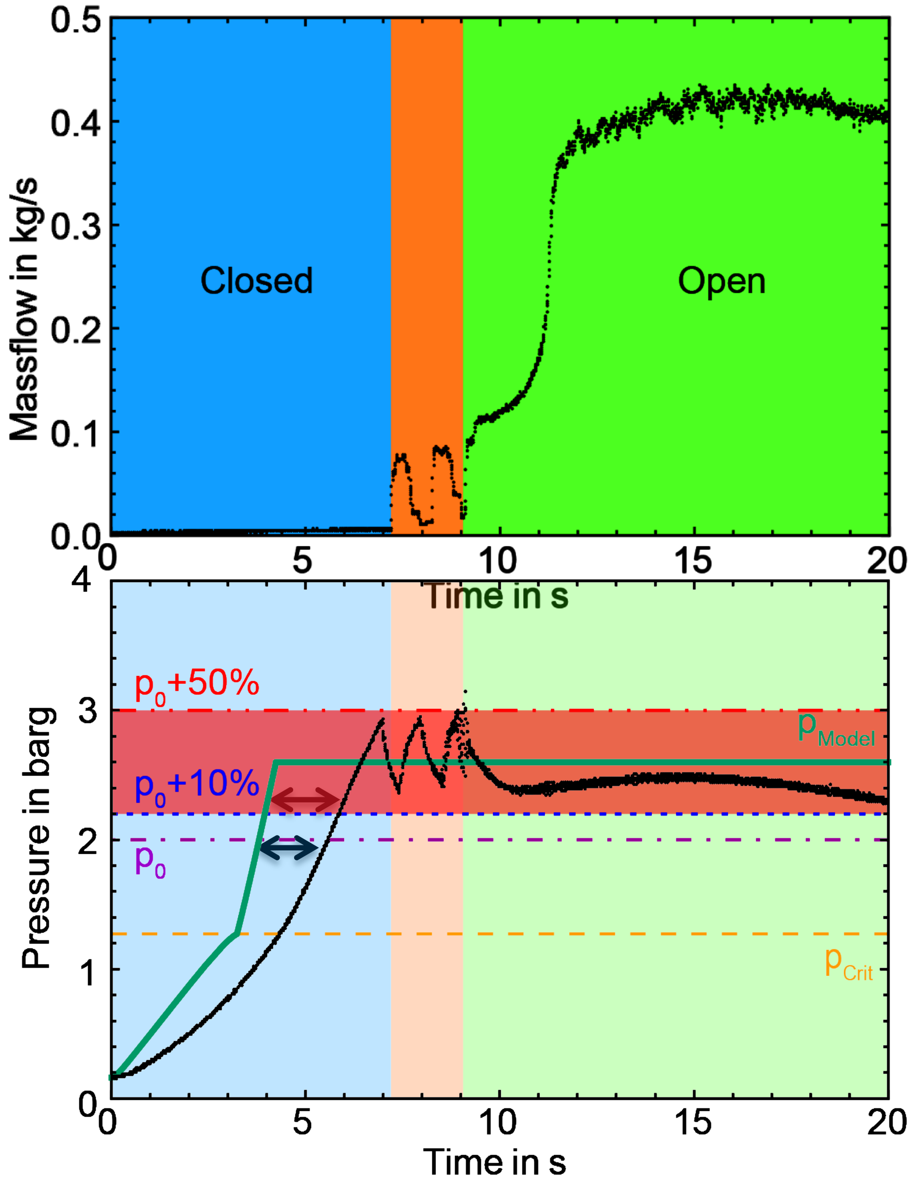
Results of First Venting Experiments

- Venting with atmospheric air
- Venting diameter: $12.5\ \mathrm{mm}$
- Set pressure safety valve: $2\ \mathrm{barg}$
- Filling level: $\sim 50\%$
- Liquid He volume: $59\ \mathrm{l}$





Thank you for your attention!

Dimensions PICARD

Component	Parameter	Value
Inner vessel	Height	900 mm
	Diameter	400 mm
	Typical liquid volume	100 l
	Nominal pressure	16 bar(g)
Outer vessel	Height	1500 mm
	Diameter	600 mm
	Nominal pressure	10 bar(g)
Radiation shield	Height	1050 mm
	Diameter	500 mm
Vent line	Diameter	60 mm
Quench gas line	Diameter	100…150 mm

Expected Mass Flow Rates

- Only vacuum insulation
- $\dot{q} = 3{,}8$ W/cm^2 [1]
- Calculation based on [3]

Set pressure of relief device in bar (abs)	Expected mass flow in kg/s
3	3.3
5	2.3
8	1.7
10	1.5

- With 10 layers of superinsulation
- $\dot{q} = 0{,}6$ W/cm^2 [1]
- Calculation based on [3]

Set pressure of relief device in bar (abs)	Expected mass flow in kg/s
3	0.51
5	0.37
8	0.27
10	0.23

[1] W. Lehmann, and G. Zahn, “Safety aspects for LHe cryostats and LHe containers”, in PROC INT CRYOG ENG CONF, London, 1978, vol. 7, pp. 569–579
[3] Varghese, A. P., Zhang, B. X., „Capacity requirements for pressure relief devices on cryogenic containers”, in *ADV CRYOGEN ENG*, Huntsville, Alabama, 1991, Vol. 37, pp. 1487–1493

Model Development & Solution

- **Vacuum Space:**
  - Ideal gas law
  - Fluid mechanics
  - Fluid property data

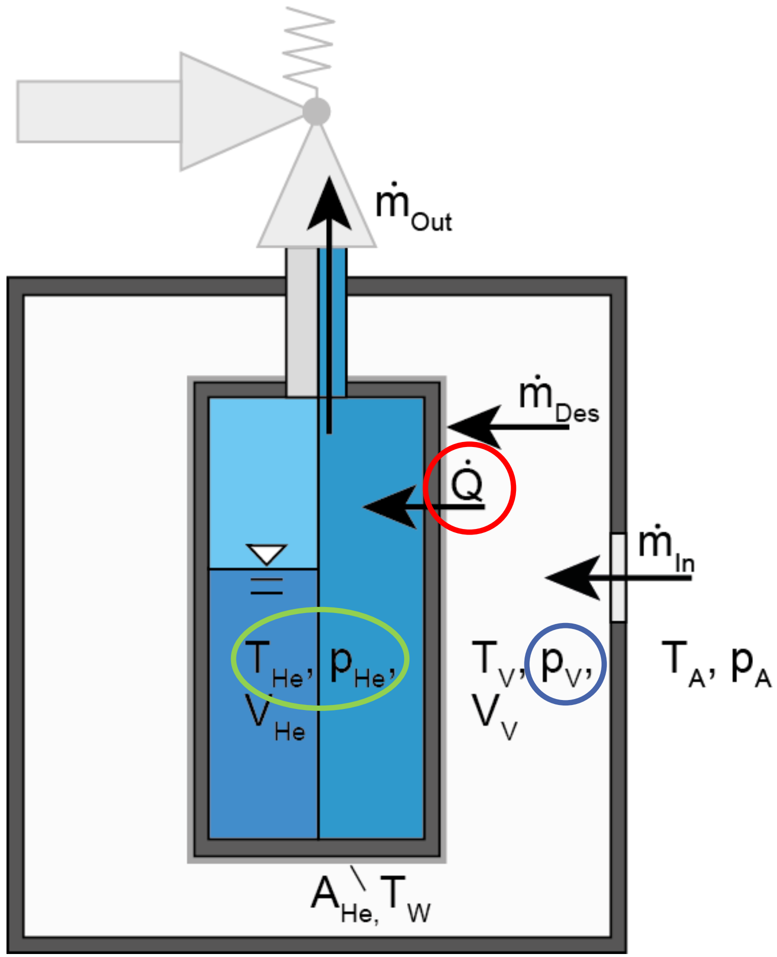
→ $p_V(\tau)$

- **Transition:**
  - Desublimation
  - Kinetics

→ $\dot{Q}(\tau)$

- **Inner Vessel:**
  - Isochoric process
    - First law of thermodynamics
    - Fluid property data
  - Isobaric process
    - First law of thermodynamics
    - Fluid mechanics
    - Fluid property data

→ $p_{He}(\tau), T_{He}(\tau)$



→ **Simultaneous numeric solution of ODEs**